

Multiwavelength monitoring of BD +53°2790, the optical counterpart to 4U 2206+54

P. Blay¹, I. Negueruela², P. Reig^{3,4}, M. J. Coe⁵, R. H. D. Corbet^{6,7}, J. Fabregat⁸, and A. E. Tarasov⁹

¹ Institut de Ciència dels Materials, Universidad de Valencia, P.O. BOX 22085, E46071 Valencia, Spain

e-mail: pere.blay@uv.es

² Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, EPSA, Universidad de Alicante, P.O. BOX 99, E03080, Alicante, Spain

e-mail: ignacio@dfists.ua.es

³ Foundation for Research and Technology-Hellas, 711 10, Heraklion, Crete, Greece

⁴ Physics Department, University of Crete, 710 03 Heraklion, Crete, Greece

e-mail: pau@physics.uoc.gr

⁵ School of Physics and Astronomy, Southampton University, Southampton, SO17 1BJ, U.K.

e-mail: M.J.Coe@soton.ac.uk

⁶ X-ray Astrophysics Laboratory, Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

⁷ Universities Space Research Association

e-mail: corbet@milkyway.gsfc.nasa.gov

⁸ Observatori Astronòmic, Universidad de Valencia, P.O. BOX 22085, E46071 Valencia, Spain

e-mail: juan@pleione.oauv.uv.es

⁹ Crimean Astrophysical Observatory, Nauchny, Crimea, 334413, Ukraine

e-mail: tarasov@crao.crimea.ua

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Abstract. We present the results of our long-term monitoring of BD +53°2790, the optical counterpart to the X-ray source 4U 2206+54. Unlike previous studies that classify the source as a Be/X-ray binary, we find that its optical and infrared properties differ from those of typical Be stars: the variability of the V/R ratio is not cyclical; there are variations in the shape and strength of the H α emission line on timescales less than 1 day; and no correlation between the EW and the IR magnitudes or colors is seen. Our observations suggest that BD +53°2790 is very likely a peculiar O9.5V star. In spite of exhaustive searches we cannot find any significant modulation in any emission line parameter or optical/infrared magnitudes. Spectroscopy of the source extending from the optical to the K-band confirms the peculiarity of the spectrum: not only are the He lines stronger than expected for an O9.5V star but also there is no clear pattern of variability. The possibility that BD +53°2790 is an early-type analogue to He-strong stars (like θ^1 Ori C) is discussed.

Key words. stars:early-type - stars:emission-line - stars:magnetic fields - stars:individual:BD+53°2790

1. Introduction

4U 2206+54, first detected by the *UHURU* satellite (Giacconi et al. 1972), is a weak persistent X-ray source. It has been observed by *Ariel V* (as 3A 2206+543; Warwick et al. 1981), *HEAO-1* (Steiner et al. 1984), *EXOSAT* (Saraswat & Apparao 1992), *ROSAT* (as 1RX J220755+543111; Voges et al. 1999), *Ross XTE* (Corbet & Peele, 2001; Negueruela & Reig 2001, henceforth NR01) and *INTEGRAL* (Blay et al., 2005). The source is variable, by a factor > 3 on timescales of a few minutes and by a factor > 10 on longer timescales (Saraswat & Apparao

1992; Blay et al. 2005), keeping an average luminosity around $L_x \approx 10^{35}$ erg s $^{-1}$ for an assumed distance of 3 kpc (NR01).

The optical counterpart was identified by Steiner et al. (1984), based on the position from the *HEAO-1* Scanning Modulation Collimator, as the early-type star BD +53°2790. The star displayed H α line in emission with two clearly differentiated peaks, separated by about 460 km s $^{-1}$. Even though some characteristics of the counterpart suggested a Be star (Steiner et al., 1984), high resolution spectra show it to be an unusually active O-type star, with an approximate spectral type O9Vp (NR01).

RossixTE/ASM observations of 4U 2206+54, show the X-ray flux to be modulated with a period of approximately 9.6 days (see Corbet & Peele, 2001; Ribó et al., 2005). The short orbital period, absence of X-ray pulsations and peculiar optical counterpart make 4U 2206+54 a rather unusual High-Mass X-ray Binary (HMXB). The absence of pulsations indicates that the compact companion could be a black hole. Recent studies of high energy emission from the system, however, suggest that the compact object in 4U2206+54 is a neutron star (Blay et al., 2005; Torrejón et al. 2004; Masseti et al. 2004).

In an attempt to improve our knowledge of this system, we have collected optical and infrared observations covering about 14 years.

2. Observations

We present data obtained as a part of a long-term monitoring campaign consisting of optical and infrared spectra, infrared and optical broad-band photometry and narrow-band Strömgren optical photometry of BD +53°2790, the optical counterpart to 4U 2206+54.

2.1. Spectroscopy

2.1.1. Optical Spectroscopy

We have monitored the source from 1990 to 1998, using the 2.5-m Isaac Newton Telescope (INT) and the 1.0-m Jakobus Kapteyn Telescope (JKT), both located at the Observatorio del Roque de los Muchachos, La Palma, Spain, and the 1.5-m telescope at Palomar Mountain (PAL). We have also made use of data from the La Palma Archive (Zuiderwijk et al. 1994). The archival data consist of H α spectroscopic observations taken with the INT over the period 1986–1990. The two datasets overlap for a few months and together they constitute continuous coverage of the source for thirteen years. The older INT observations had been taken with the Intermediate Dispersion Spectrograph (IDS) and either the Image Photon Counting System (IPCS) or a CCD camera. All the INT data after 1991 were obtained with CCD cameras. The JKT observations were obtained using the St Andrew’s Richardson-Brealey Spectrograph (RBS) with the R1200Y grating, the red optics and either the EEV7 or TEK4 CCD cameras, giving a nominal dispersion of ≈ 1.2 Å. The Palomar 1.5-m was operated using the f/8.75 Cassegrain echelle spectrograph in regular grating mode (dispersion ≈ 0.8 Å/pixel).

Further observations were taken with the 2.6-m telescope at the Crimean Astrophysical Observatory (CRAO) in Ukraine.

From 1999, further monitoring has been carried out using the 1.52-m G. D. Cassini telescope at the Loiano Observatory (BOL), Italy, equipped with the Bologne Faint Object Spectrograph and Camera (BFOSC) and the 1.3-m Telescope at the Skinakas Observatory (SKI), in Crete, Greece. From Loiano, several observations were

taken using grism#8, while higher resolution spectra were taken with grism#9 in echelle mode (using grism#10 as cross-disperser). Other spectra were taken with the echelle mode of grism#9 and grism#13 as cross-disperser, giving coverage of the red/far-red/near-IR region (up to ~ 9000 Å). At Skinakas, the telescope is an f/7.7 Ritchey-Cretien, which was equipped with a 2000×800 ISA SITE chip CCD and a 1201 line mm^{-1} grating, giving a nominal dispersion of 1 Å pixel $^{-1}$.

Blue-end spectra of the source have also been taken with all the telescopes listed, generally using the same configurations as in the red spectroscopy, but with blue gratings and/or optics when the difference was relevant (for example, from Loiano, grisms #6 and #7 were used for the blue and yellow regions respectively).

All the data have been reduced using the *Starlink* software package FIGARO (Shortridge et al., 1997) and analysed using DIPSO (Howarth et al., 1997). Table 5 lists a log of the spectroscopic observations.

2.1.2. Infrared Spectroscopy

Near-infrared (*I* band) spectra of BD +53°2790 have also been taken with the JKT, INT and G. D. Cassini telescopes.

K-band spectroscopy of BD +53°2790 was obtained on July 7-8, 1994, with the Cooled Grating Spectrometer (CGS4) on UKIRT, Hawaii. The instrumental configuration consisted of the long focal station (300 mm) camera and the 75 lines mm^{-1} grating, which gives a nominal velocity resolution of 445 km s^{-1} at $2\mu\text{m}$ ($\lambda/\Delta\lambda \approx 700$). The data were reduced according to the procedure outlined by 1993.

2.2. Photometry

2.2.1. Optical Photometry

We took one set of *UBVRI* photometry of the source on August 18, 1994, using the 1.0-m Jakobus Kapteyn Telescope (JKT). The observations were made using the TEK#4 CCD Camera and the Harris filter set. The data have been calibrated with observations of photometric standards from Landolt et al. (1992) and the resulting magnitudes are on the Cousins system.

We also obtained several sets of Strömgren *uvby* photometry. The early observations were taken at the 1.5-m Spanish telescope at the German-Spanish Calar Alto Observatory, Almería, Spain, using the *UBVRI* photometer with the *uvby* filters, in single-channel mode, attached to the Cassegrain focus. Three other sets were obtained with the 1.23-m telescope at Calar Alto, using the TEK#6 CCD equipment. One further set was taken with the 1.5-m Spanish telescope equipped with the single-channel multipurpose photoelectric photometer. Finally, one set was obtained with the 1.3-m Telescope at Skinakas, equipped with a Tektronik 1024×1024 CCD.

All observations are listed in Table 1.

Table 2. Measurement of the EW of strong absorption lines (without obvious variability and presumably photospheric) in the spectrum of BD +53°2790.

| Line | EW (Å) |
|--------------------------------|--------|
| He II $\lambda 4200\text{\AA}$ | 0.4 |
| H γ | 2.2 |
| He I $\lambda 4471\text{\AA}$ | 1.3 |
| He II $\lambda 4541\text{\AA}$ | 0.4 |
| He I $\lambda 4713\text{\AA}$ | 0.5 |
| He I $\lambda 4923\text{\AA}$ | 0.7 |

2.2.2. Infrared Photometry

Infrared observations of BD +53°2790 have been obtained with the Continuously Variable Filter (CVF) on the 1.5-m. Carlos Sánchez Telescope (TCS) at the Teide Observatory, Tenerife, Spain and the UKT9 detector at the 3.9-m UK Infrared Telescope (UKIRT) on Hawaii. All the observations are listed in Table 6. The errors are much smaller after 1993, when we started implementing the multi-campaign reduction procedure described by Manfroid (1993).

3. Long-term monitoring

3.1. Spectrum description and variability

?? Spectra in the classification region (4000–5000 Å) show all Balmer and He I lines in absorption. Several spectra of BD+53°2790 at moderately high resolution were presented in NR01, together with a detailed discussion of its spectral peculiarities. A representative spectrum covering a wider spectral range is given in Fig. 1. The rather strong He II $\lambda 5412\text{\AA}$ line represents further confirmation that the underlying spectrum is that of an O-type star. Together with the blue spectrum of BD+53°2790 a spectrum of the O9V standard 10 Lac is also shown in Fig. 1.

There is no evidence for variability in what can be considered with certainty to be photospheric features (i.e., the Balmer lines from H γ and higher and all He I and He II lines in the blue). However, it must be noted that the EW of H γ is $\approx 2.2\text{\AA}$ in all our spectra (and this value should also include the blended O II $\lambda 4350\text{\AA}$ line), which is too low for any main sequence or giant star in the OB spectral range (Balona & Crampton 1974). Average values of EWs for different lines are indicated in Table 2. The main spectral type discriminant for O-type stars is the ratio He II $\lambda 4541\text{\AA}$ /He I $\lambda 4471\text{\AA}$. The quantitative criteria of Conti & Alschuler (1971), revised by Mathys (1988), indicate that BD +33°2790 is an O9.5 V star, close to the limit with O9 V.

Representative shapes of the H α line in BD +53°2790 are shown in Fig. 2. In all the spectra, two emission components appear clearly separated by a deep narrow central reversal. The absorption component normally extends well below the local continuum level – which is usually referred

to as a “shell” spectrum – but in some spectra, it does not reach the continuum. The red (R) peak is always stronger than the blue (V) peak, but the V/R ratio is variable.

The first case of observed strong variability happened during 1986, when the profile was observed to have changed repeatedly over a few months from a shell structure to a double-peaked feature, with the central absorption not reaching the continuum level. The second one took place in 1992, when the strength of the emission peaks decreased considerably to about the continuum level. Finally, during the summer of 2000, we again saw line profiles in which the central absorption hardly reached the continuum level alternating with more pronounced shell-like profiles.

Figure 3 displays a plot of the Full Width at Half Maximum (FWHM), V/R and peak separation (ΔV) of the H α line against its EW, for all the data from the INT. H α parameters (EW, FWHM, V/R and ΔV) were obtained for all the datasets shown in Table 5. Given the very diverse origins of the spectra and their very different spectral resolutions, it is difficult to compare them all, as there are some effects which introduce some artificial scattering in the data. This is the case of the instrumental broadening affecting the FWHM. At a first approximation we considered that it was not necessary to account for it. Taking into account the typical spectral resolutions of our dataset –better than 3\AA in most cases– and the fact that for the majority of our spectra FWHM $> 11\text{\AA}$ (and generally $\approx 14\text{\AA}$), the instrumental broadening, a priori, can be considered negligible. Dachs et al. (1986) found a correlation between H α parameters (FWHM, peak separation, EW) in Be stars. We fail to see these correlations when the entire set of spectra is used but they are present when we restrict the analysis to those spectra taken with the same instrument, see Fig. 3. There is, however, a large spread in the case of the V/R ratio. Most of the scatter in FWHM may be related to the larger uncertainties involved when the emission components are small and the line profile is separated.

Red spectra covering a larger wavelength range (such as that in Fig. 5) show also the He I $\lambda 6678\text{\AA}$ line and sometimes the He I $\lambda 7065\text{\AA}$ line. Like H α , the He I $\lambda 6678\text{\AA}$ line typically displays a shell profile, but the emission peaks are weaker than those of H α , while the central absorption component is normally very deep. Variability in this line is also more frequent than in H α . The V peak is generally dominant, but the two peaks can be of approximately equal intensities and sometimes so weak that they cannot be distinguished from the continuum. Given the apparent different behaviour of H α and He I $\lambda 6678\text{\AA}$ lines, it is surprising to find that there is some degree of correlation between their parameters, as can be seen in Fig. 4, where EW of both lines from INT spectra in which both lines were visible are shown.

The upper Paschen series lines are always seen in absorption and no variability is obvious (see Fig. 5). The Paschen lines are much deeper and narrower than those observed in main-sequence OB stars

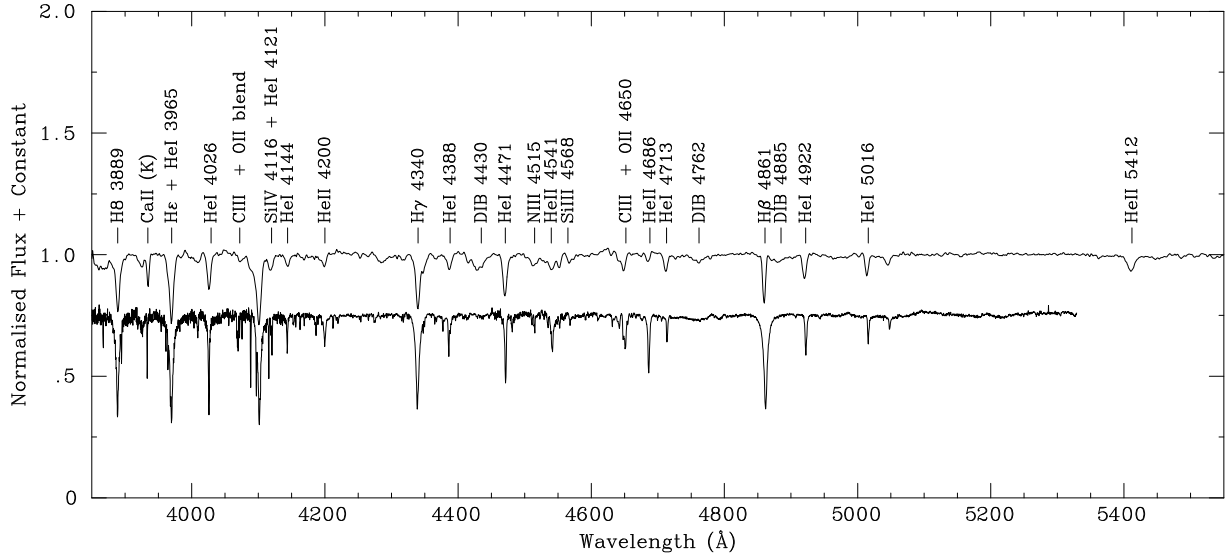


Fig. 1. Blue/green spectrum of BD +53°2790, taken on July 21, 2000 with the 1.3-m telescope at Skinakas. Only the strongest features have been indicated. For a more complete listing of photospheric features visible in the spectrum, see NR01. The spectrum has been normalised by dividing a spline fit into the continuum. A normalised spectrum of 10 Lac (09V), shifted down for plotting purposes, is also shown for comparison.

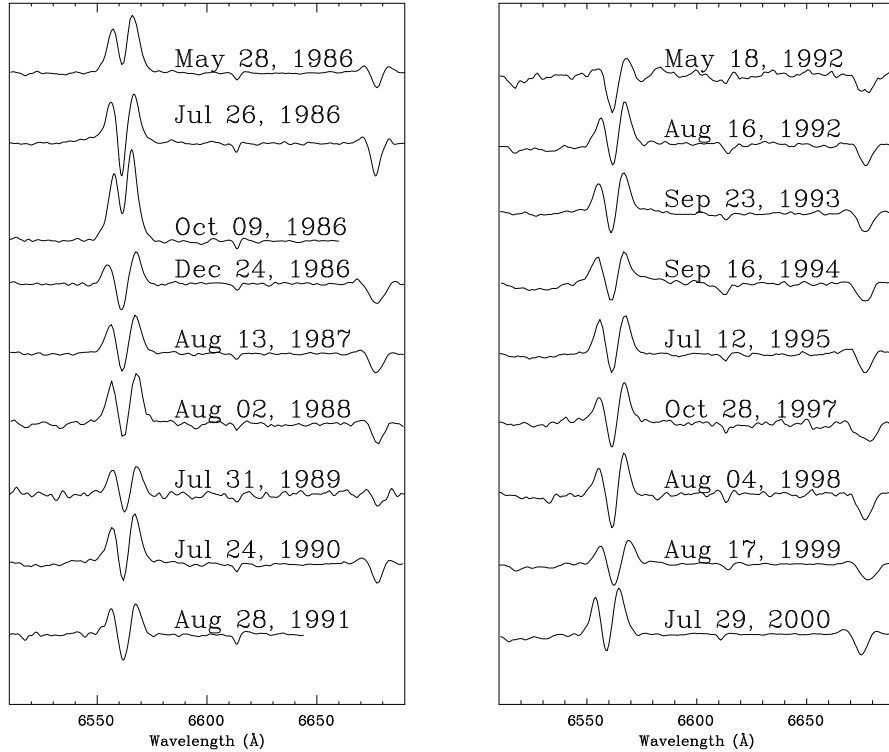


Fig. 2. Evolution of the H α line profile of BD +53°2790 during 1986–2000. All spectra have had the continuum level normalised and are offset vertically to allow direct comparison.

by Andrillat et al. (1995) and rather resemble early B-type supergiant stars. However, it must be noted that some shell stars in the low-resolution catalogue of Andrillat et al. (1988) display *I*-band spectra that share some characteristics with that of BD +53°2790.

K-band spectra are shown in Fig. 6. Unlike the OB components of several Be/X-ray binaries observed by Everall et al. (1993; see also Everall 1995), BD +53°2790 shows no emission in He I λ 2.058 μ m (though the higher resolution spectrum suggests a weak shell profile). Br γ

may have some emission component, but is certainly not in emission. The situation differs considerably from that seen in the K -band spectrum of BD +53°2790 presented by Clark et al. (1999), taken on 1996 October. There Br γ

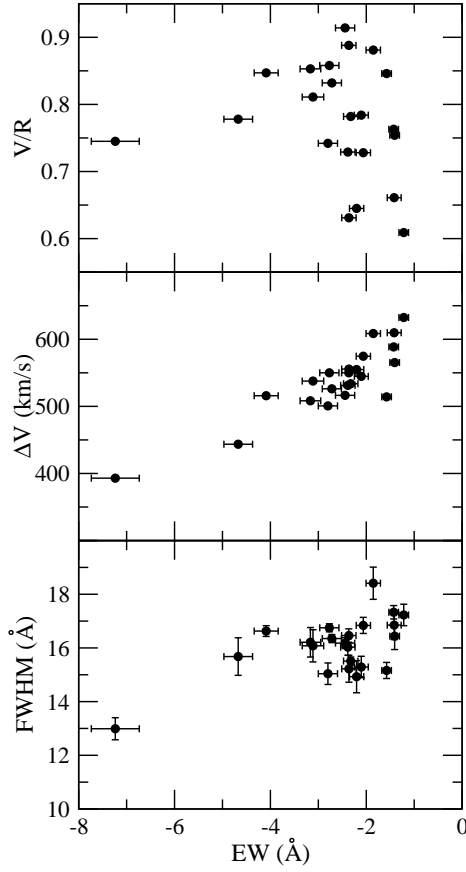


Fig. 3. Parameters of the H α emission line for all the red spectra from the INT.

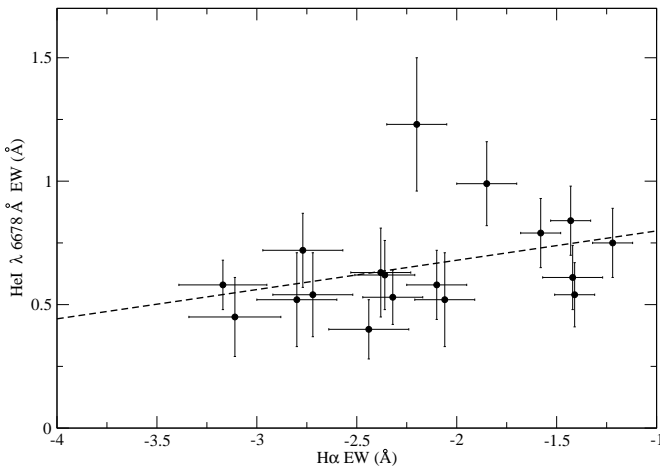


Fig. 4. EW of the He I $\lambda 6678\text{\AA}$ line versus that of the H α line. There seems to be some degree of correlation between both quantities. Only data from INT spectra where both lines were visible are shown. A linear regression fit to the data is shown as a dashed line. The correlation coefficient of the regression is $r=0.62$ and the correlation is significant at a 98% confidence level.

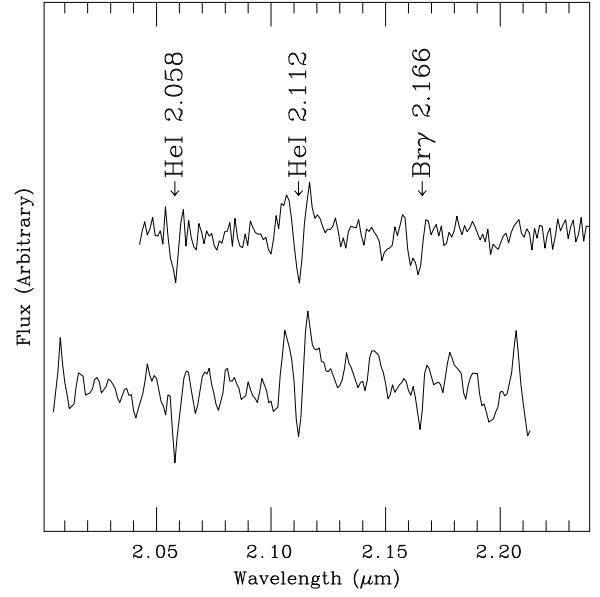


Fig. 6. K -band spectra of BD +53°2790. The top spectrum was taken on July 7 1994, and the bottom one on July 8 1994.

displays a clear shell profile with two emission peaks and He I $\lambda 2.112\text{ }\mu\text{m}$ is in absorption. This shows that the shell-like behaviour and variability extends into the IR.

3.2. Photometric evolution and colours

The $UBVRI$ photometric values we obtain are $U = 9.49$, $B = 10.16$, $V = 9.89$, $R = 9.88$ and $I = 9.55$. The photometric errors are typically 0.05 mag, derived from the estimated uncertainties in the zero-point calibration and colour correction. Table 1 lists our Strömgren $uvby\beta$ measurements.

V measurements in the literature are scarce and consistent with being constant (see references in NR01). However, our more accurate set of measurements of the V magnitude (or Strömgren y) show variability, with a difference between the most extreme values of 0.13 ± 0.05 mag (see Table 1), 0.05 mag being also the standard deviation of all 7 measurements.

From our UBV photometry, we find that the reddening-free parameter Q ($Q = -0.72(B - V) + (U - B)$) is $Q = -0.86 \pm 0.10$. This value corresponds, according to the revised Q values for Be and shell stars calculated by Halbedel (1993), to a B1 star.

We have tried deriving the intrinsic parameters of BD +53°2790 from our Strömgren photometry by applying the iterative procedure of Shobbrook (1983) for dereddening. The values obtained for the reddening from the different measurements agree quite well to $E(b - y) = 0.38 \pm 0.02$ (one standard deviation) and the colour $(b - y)_0$ averages to -0.12 ± 0.02 . This value corresponds to a B1V star according to the calibrations of Perry et al. (1987) and Popper (1980).

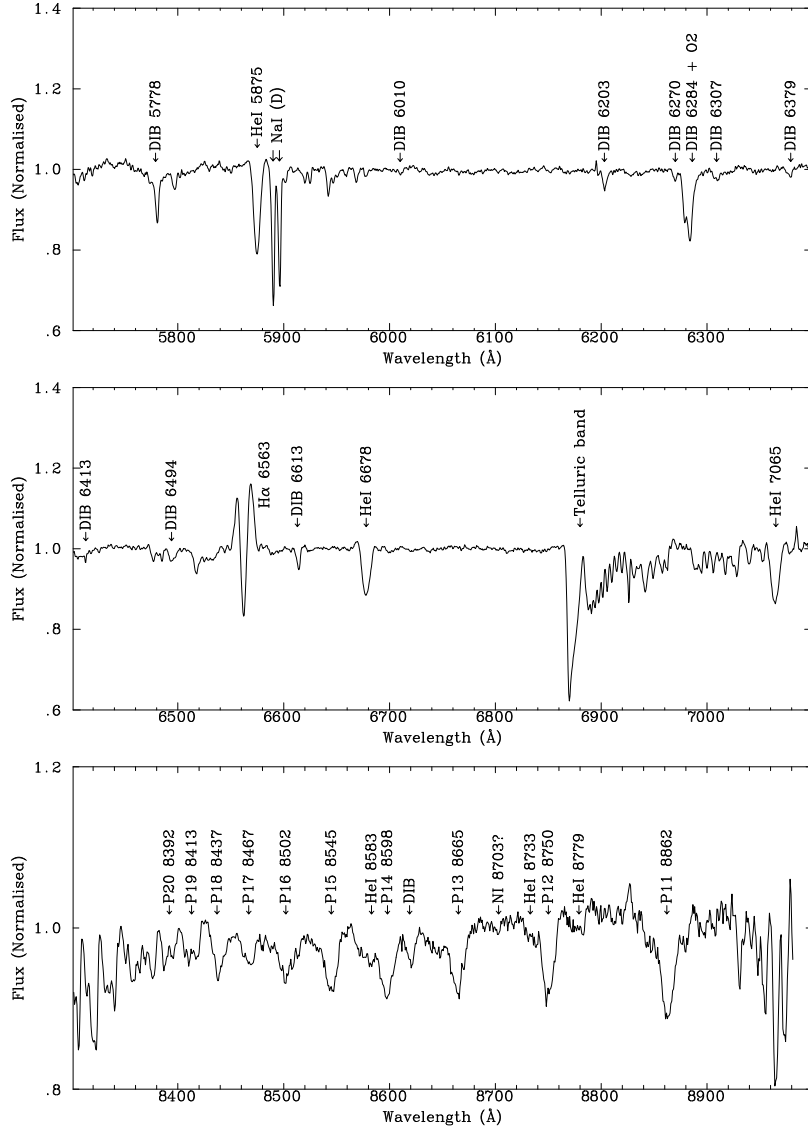


Fig. 5. The spectrum of BD +53°2790 in the yellow/red/near-IR. Echelle spectrum taken on 17th August 1999 using the 1.52-m G. D. Cassini Telescope equipped with BFOSC and grisms #9 (echelle) and #13 (cross-disperser). All the orders have been flattened by division into a spline fit to the continuum.

Our infrared photometry coverage extends for ≈ 13 yr and is much more comprehensive than our optical photometry. The IR long-term light curve is shown in Fig. 7. Data have been binned so that every point represents the average of all the nights in a single run (excluding those with unacceptably large photometric errors).

As can be seen in Fig. 7, the range of variability is not very large, with extreme values differing by ≈ 0.2 mag in all three bands. Variability seems to be relatively random, in the sense that there are no obvious long-term trends. The light curves for the three infrared magnitudes are rather similar in shape, suggesting that the three bands do not vary independently.

In spite of this, all colour-magnitude plots are dominated by scatter. Moreover, an analysis of the temporal behaviour shows that there is no obvious pattern in the evolution of the source on the $H/(H-K)$ and $K/(H-K)$

planes, with frequent jumps between very distant points and no tendency to remain in any particular region for any length of time.

The only plot in which a clear correlation stands out is the $K/(H-K)$ diagram (see Fig. 8). In principle, one would be tempted to dismiss this correlation as the simple reflection of stronger variability in K than in H , since $(H-K)$ would necessarily be smaller for larger values of K . However a linear regression of H against K also shows a clear correlation. We find $a = 0.89$, $b = 0.93$ and a correlation coefficient of $r^2 = 0.64$ for $K = aH + b$. Suspecting, then, that linear correlation must be present in the $H/(H-K)$ plot as well, we also performed a linear regression. In this case we found a very poor correlation.

Equally disappointing is the search for correlations between the EW of H α and the $(J-K)$ color. Even though our measurements of these two quantities are not simulta-

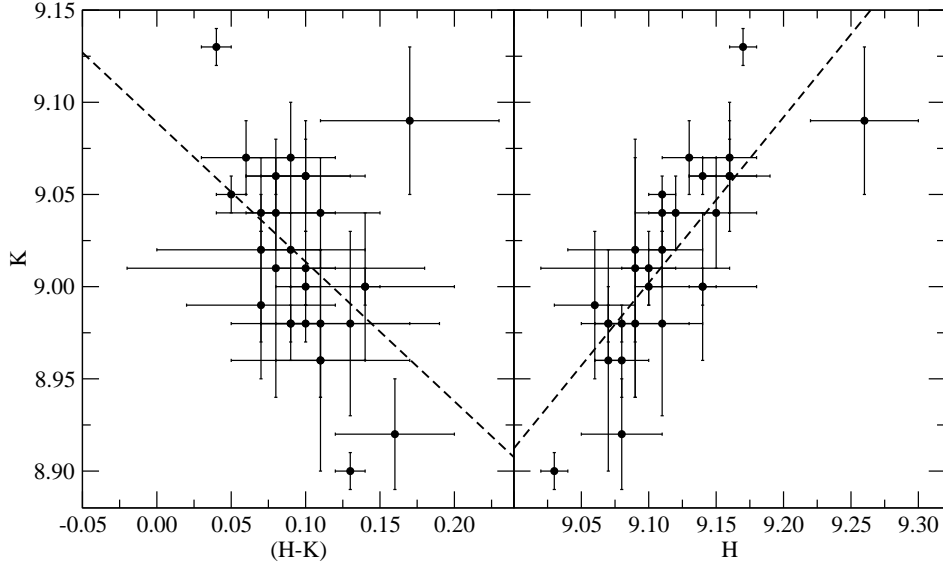


Fig. 8. Colour-magnitude plots showing the evolution of the infrared magnitudes. The strong correlation seen in the $K/(H-K)$ plane is not a simple reflection of the fact that a brighter K means a smaller $(H-K)$, as the correlation between H and K is also strong. Regression lines are shown as dashed lines. In the first case the correlation coefficient is $r_{(H-K),K} = -0.46$ and the correlation is significant in a 98% confidence level. In the latter case the correlation coefficient is $r_{H,K} = 0.80$ and the correlation is also significant at a 98% confidence level.

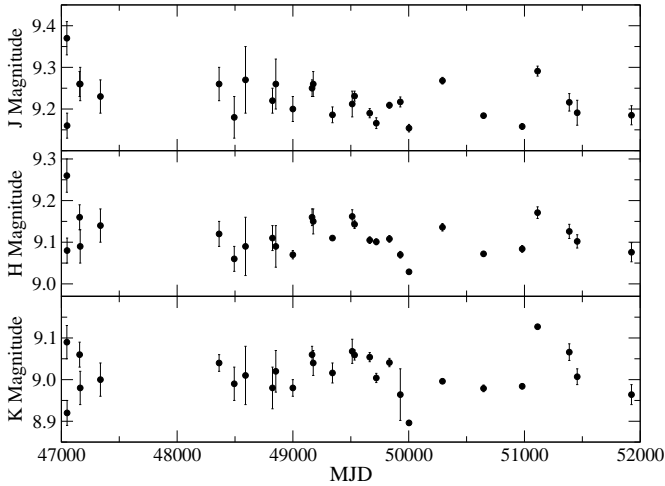


Fig. 7. Infrared light curves of BD +53°2790, taken during 1987–2001.

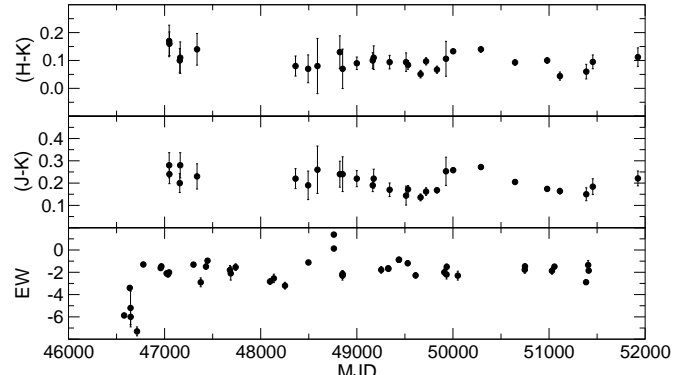


Fig. 9. Evolution of the infrared colours in BD +53°2790 during 1987–1999 compared to that of the EW of $H\alpha$. Since simultaneous measurements are rare, we cannot properly search for correlations. The lack of any obvious correlated trends could be caused by the lack of long-term trends.

neous, a look at their respective evolutions (Fig. 9) shows no clear correlation.

3.3. Periodicity searches

All the parameters of the $H\alpha$ emission line are clearly variable: EW, FWHM, V/R ratio and peak separation. In the hope that the variation in any of these parameters could give us information about the physical processes causing them, we have searched the dataset for periodicities. The large variety of resolutions, CCD configurations and S/N ratios present in the data have hampered our attempts at a homogeneous and coherent analysis. We have made an effort, within the possibilities of the dataset, to use the

same criteria to measure all parameters on all spectra. We have used several different algorithms (CLEAN, Scargle, PDM) in order to detect any obvious periodicities, but with no success. No sign of any significant periodicity has been found in any of the trials.

Likewise, we have explored possible periodicities in the infrared light curves. While the J , H and K magnitudes seem to vary randomly, we find a striking apparent modulation of the $(J-K)$ colour. Figure 9 shows an obvious trend in the evolution of $(J-K)$, with a suggestion that the variability (with an amplitude ~ 0.2 mag) may be (quasi-)periodic over a very long timescale, on the order of ~ 5 y. Unfortunately, this timescale is too long compared to our coverage to allow any certainty.

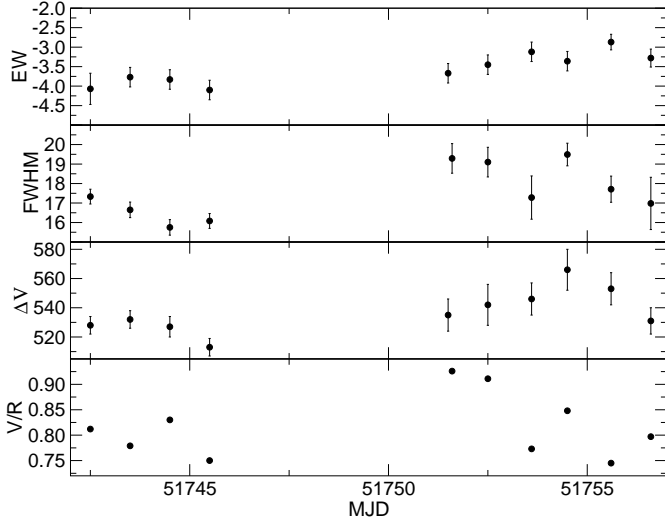


Fig. 10. $H\alpha$ parameters – EW (in Å), FWHM (in Å), peak separation (in km s^{-1}) and V/R ratio– for the monitoring campaign in July 2000. There seems to be a high degree of correlation in the evolution of EW, FWHM and peak separation, which is not shared by the V/R ratio.

We have also folded the data using the period detected in the analysis of the X-ray light curve of 4U 2206+54 (the presumably orbital 9.56-d period, see Corbet & Peele, 2001 and Ribó et al. 2005), without finding any significant periodic modulation.

4. Intensive monitoring during the summer of 2000

Considering the possibility that the lack of detectable periodicities in our dataset was due to the varying resolutions and irregular time coverage, during July 2000 we carried out more intensive spectroscopic monitoring of BD +53° 2790. Observations were made from Skinakas (Crete) and Loiano (Italy). We collected a set of 2 to 5 spectra per night during two runs: from 17th to 20th July in Skinakas and from 26th to 31st July in Loiano. The instrumental configurations were identical to those described in Section 2.

We fear that one of our objectives, the study of possible orbital variations, may have been affected by an observational bias. The presumed orbital period of the source is 9.56 days, probably too close to the time lag (10 days) between the first observing night at Skinakas and the first observing night at Loiano. Therefore we have not been able to cover the whole orbital period. Indeed, the phases (in the 9.56 d cycle) at which the observations from Skinakas were taken, were almost coincident with the phases during the first four Loiano nights. For this reason, our coverage of the orbital period extends to only $\approx 60\%$, which is insufficient to effectively detect any sort of modulation of any parameters at the orbital period.

Again, we have measured all parameters of the $H\alpha$ line, which are shown in Fig 10. Contrary to what we saw when considering the dataset for the 13 previous years, we

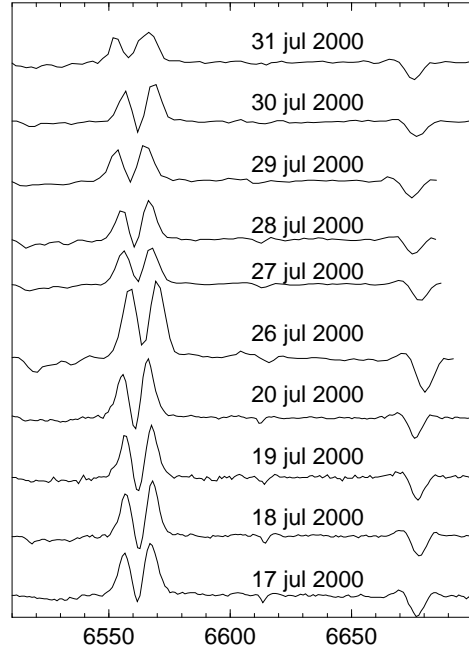


Fig. 11. Evolution of $H\alpha$ line in BD +53°2790 during the monitoring campaign in July 2000. Note the moderate night-to-night changes of the line profile and the important difference between the spectra from the first and second week.

find some degree of correlation between EW, FWHM and ΔV , while V/R seems to vary independently. Since this correlation between the different line parameters seems natural, we attribute the lack of correlations within the larger dataset to the use of data of very uneven resolution and quality.

We observe obvious changes in the depth of the central absorption core in the $H\alpha$ line, which is seen sometimes reaching below the continuum level, while in other occasions is above the continuum (see Fig 11). Similar behaviour had already been observed in 1986 (see Fig. 2, but no further examples are found in our data sample). Lines in the blue (3500–5500 Å) are much more stable, as is also the case when the longer term is considered. In this spectral range, the spectra resemble closely those obtained at other epochs, with weak emission components visible in $\text{He II } \lambda 4686\text{Å}$ and $\text{H}\beta$.

5. Discussion

5.1. Reddening and distance to BD +53° 2790

The reddening to BD +53°2790 can be estimated in several different ways. Photometrically, from our value of $E(b - y) = 0.38 \pm 0.02$, using the correlation from Shobbrook (1983), we derive $E(B - V) = 0.54 \pm 0.05$. An independent estimation can be made by using the standard relations between the strength of Diffuse Interstellar Bands (DIBs) in the spectra and reddening (Herbig 1975). Using all the spectra obtained from the Cassini telescope (for consistency), we derive $E(B - V) = 0.57 \pm 0.06$ from the $\lambda 6613\text{Å}$ DIB and $E(B - V) = 0.62 \pm 0.05$ from the

$\lambda 4430\text{\AA}$ DIB. All these values are consistent with each other, therefore we take the photometric value as representative of the reddening to BD +53°2790.

From five *UBV* measurements available in the literature (including the one presented in this work), we find $(B - V) = 0.28 \pm 0.02$. With the $E(B - V)$ derived, this indicates an intrinsic colour $(B - V)_0 = -0.26 \pm 0.05$, typical of an early-type star, confirming the validity of the reddening determination. As discussed in NR01, the value of the absorption column derived from all X-ray observations is one order of magnitude larger than what is expected from the interstellar reddening. This affirmation stands also when we consider the more accurate measurement of the absorption column (i.e., $\sim 1.0 \times 10^{22} \text{ cm}^{-2}$) from *BeppoSax* data (Torrejón et al, 2004; Masseti et al, 2004).

Averaging our 7 measurements of y with the 5 V measurements, we find a mean value for BD +53°2790 of $V = 9.88 \pm 0.04$. Assuming a standard reddening law ($R = 3.1$), we find $V_0 = 8.21$. If the star has the typical luminosity of an O9.5V star ($M_V = -3.9$, see Martins et al. 2005), then the distance to BD +53°2790 is $d \approx 2.6$ kpc. This is closer than previous estimates (cf. NR01), because the absolute magnitudes of O-type stars have been lowered down in the most recent calibrations.

5.2. Why BD +53°2790 is not a classical Be star

Since its identification with 4U 2206+54, BD +53°2790 has always been considered a classical Be star, because of the presence of shell-like emission lines in the red part of its spectrum. However, the main observational characteristics of BD +53°2790 differ considerably from those of a classical Be star:

- The $H\alpha$ emission line presents a permanent (at least stable during 15 years) V<R asymmetry. Changes in the V/R ratio are not cyclical, as in classical Be stars undergoing V/R variability because of the presence of global one-armed oscillations (see Okazaki 2000). Moreover, the asymmetry survives large changes in all the other parameters of the emission line and is also present when there is basically no emission, which in a classical Be star would correspond to a disc-less state. This behaviour is fundamentally different of that seen in Be/X-ray binaries, where discs undergo processes of dispersion and reformation during which they develop instabilities that lead to long-term quasi-cyclical V/R variability (e.g., Negueruela et al. 2001 and Reig et al. 2000).
- In BD +53°2790 we observe strong night-to-night variability in both the shape and intensity of the $H\alpha$ emission line. These variations affect both the strength of the emission peaks and the depth of the central absorption component. If the emission line did arise from an extended quasi-Keplerian disc (as in Be stars), such variations would imply global structural changes of the disc on timescales of a few hours and/or ma-

jor changes in the intrinsic luminosity of the O star. Such behaviour is unprecedented in a Be star, where the circumstellar disc is believed to evolve on viscous timescales, on the order of months (Lee et al. 1991; Porter 1997).

- Be stars display a clear correlation between the EW of $H\alpha$ and the infrared excess and between the infrared magnitudes and infrared colours, which reflect the fact that emission lines and infrared excess are produced in an envelope that adds its emission to that of the star, e.g., Dachs & Wamsteker (1982). Such correlations are not readily detected in BD +53°2790. The evolution of observables (both IR magnitudes and $H\alpha$ line parameters) lacks any clear long-term trends. The star's properties may be described to be highly variable on short timescales and very stable on longer timescales, without obvious long-term variations (except for, perhaps, the $(J - K)$ colour).
- Photometrically, Be/X-ray systems are characterised by large variations in both magnitudes and to a lesser extent in colour (e.g, Negueruela et al. 2001; Clark et al. 1999 and Clark et al. 2001b), associated with the periods of structural changes in their circumstellar discs. In contrast, the magnitudes and colours of BD +53°2790 remain basically stable, with small random fluctuations, as is typical of isolated O-type stars.

As a matter of fact, the only High-Mass X-ray Binary presenting some similarities to BD +53°2790 in its photometric behaviour is LS 5039/RX J1826.2–1450. As BD +53°2790, it displays little variability in *UBV* and moderate variability in the infrared magnitudes, see Clark et al. (2001a). RX J1826.2–1450 is believed to be, like 4U 2206+54, powered by accretion from the wind of a main-sequence O-type star; see McSwain & Gies (2002), Ribó et al (1999) and Reig et al. (2003).

5.3. What is BD +53°2790?

We estimate that the most likely spectral classification of BD +53°2790 is O9.5Vp. However some remarkable peculiarities have been noticed: while the blue spectrum of BD +53°2790 suggests an O9.5 spectral type, there are a few metallic lines reminiscent of a later-type spectrum (see NR01); the UV lines support the main sequence luminosity classification, but the Paschen lines resemble those of a supergiant.

In order to obtain a measure of the rotational velocity of BD +53°2790 we have created a grid of artificially rotationally broadened spectra from that of the standard O9V star 10 Lac. We have chosen 10 Lac because of its very low projected rotational velocity and because the spectrum of BD +53°2790 is close to that of a O9V star. In Fig. 12 normalised profiles of a set of selected helium lines (namely, He I $\lambda 4026$, $\lambda 4144$, $\lambda 4388$, and $\lambda 4471$ Å) are shown together with the artificially broadened profile of 10 Lac, at 200 km s^{-1} and those rotational velocities producing upper and lower envelopes to the widths of the

Table 3. Summary of the measured rotational velocities for the selected helium lines shown in Fig. 12.

| Line (Å) | Rot. Vel. (km s ⁻¹) | Average (km s ⁻¹) |
|---------------------|------------------------------------|----------------------------------|
| He I λ 4026 | 280 | 320 \pm 40 |
| | 360 | |
| He I λ 4144 | 320 | 350 \pm 30 |
| | 380 | |
| He I λ 4388 | 260 | 290 \pm 30 |
| | 320 | |
| He I λ 4471 | 260 | 300 \pm 40 |
| | 340 | |

observed profiles of BD +53°2790. The rotational velocity of BD +53°2790 must be above 200 km s⁻¹. For each line, the average of the rotational velocities yielding the upper and lower envelopes were taken as a representative measurement of the rotational velocity derived from that line. The results of these measurements are summarised in Table 3. We estimated the averaged rotational velocity of BD +53°2790 to be 315 \pm 70 km s⁻¹.

Comparison of the helium profiles with those rotationally broadened from 10 Lac shows that the observed helium profiles in BD +53°2790 are stronger than what is expected for a normal O9.5V star. The strength of the He lines suggests the possibility that BD +53°2790 may be related to the He-strong stars. These are a small group of stars, with spectral types clustering around B2 V, that show anomalously strong helium lines. A well known O-type star believed to be related to He-strong stars is θ^1 Ori C, which is known to vary in spectral type from O6 to O7 (Donati et al. 2002, Smith & Fullerton 2005). BD +53°2790 could be the second representative of this class of objects among O-type stars. He-strong stars display a remarkable set of peculiarities: oblique dipolar magnetic fields, magnetically controlled winds, and chemical surface anomalies, among others. Usually these stars are distributed along the ZAMS (Pedersen & Thomsen, 1997; Walborn, 1982; Bohlender et al. 1987; Smith & Groote 2001).

A rich variety of phenomena have been observed in these objects: in the UV, they can show red shifted emission of the C IV and Si IV resonance lines (sometimes variable); in the optical bands they are characterized by periodically modulated H α emission, high level Balmer lines appearing at certain rotational phases and periodically modulated variability in He lines, sometimes showing emission at He II λ 4686 Å. They can also show photometric variability with eclipse-like light curves.

Except for the periodic modulation of the variations, BD +53°2790 shares many of these peculiarities. In particular, together with the apparent high helium abundance, BD +53°2790 shows variable H α emission and He II λ 4686 Å emission, the UV spectrum shows apparently prominent P-Cygni profiles at C IV and Si IV resonance lines (see NR01). In contrast a wind slower than expected is found (see Ribó et al. 2005), which can be an

indication of some red-shifted excess of emission in these lines. In He-strong stars the wind is conducted along the magnetic field lines into a torus-like envelope located at the magnetic equator. This configuration can lead to the presence of double emission peaks in H α , which resemble those seen in BD +53°2790, but which usually show a modulation on the rotational period. The complexity and shape of the double peak will depend on the angle between magnetic and rotational axes and the line of sight to the observer (see Townsend et al. 2005).

A rotationally dominated circumstellar envelope is clearly present in BD +53°2790, as indicated by the infrared magnitudes, the emission in Balmer and some helium lines and the correlations between H α line parameters. However the structure of this circumstellar envelope clearly differs from those seen in Be stars. Following the analogy with He-strong stars, the existence of a circumstellar disk-like structure is also common to these type of objects also. The only difficulty to accept BD+53°2790 as a He-strong star is the apparent lack of rotational modulation of the emission lines parameters. Given the rotational velocities derived, we could expect a rotational period of a few days. In addition to the problems in the diverse origin of our data (see section ??), the sampling on time of our measurements is not adequate to find variations on time scales of a few days (modulated with the rotational period), thus we cannot discard yet the presence of rotational periodicity. The idea of a magnetically driven wind contributing to a dense disk-like structure is not strange even in the modelling of Be stars' circumstellar envelopes. The wind compressed disk of Bjorkman & Cassinelli (1992) was shown to be compatible with observations only if a magnetic field on the order of tens of Gauss was driving the wind from the polar caps onto the equatorial zone (Porter 1997).

A careful inspection to the correlation seen in Fig. 4 between the He I λ 6678 and H α EWs shows that there is a common component to the emission of both lines. H α emission, then, will have at least two contributions: a P-Cygni like contribution (as seen in the 1992 spectra, see Fig. 2, where the double peak structure disappears and only the red peak survives) and an additional variable double peaked structure. The relative variation of both components may hide any periodic modulation present.

Therefore, we can conclude that this is a very peculiar O9.5V star where most likely a global strong magnetic field may be responsible for most of the behaviour seen so far.

6. Conclusion

We have presented the results of \sim 14 years of spectroscopic and optical/infrared photometric monitoring of BD +53°2790, the optical component of the Be/X-ray binary 4U 2206+54. The absence of any obvious long-term trends in the evolution of different parameters and fundamentally the absence of correlation between the EW of H α and the infrared magnitudes and associated colours

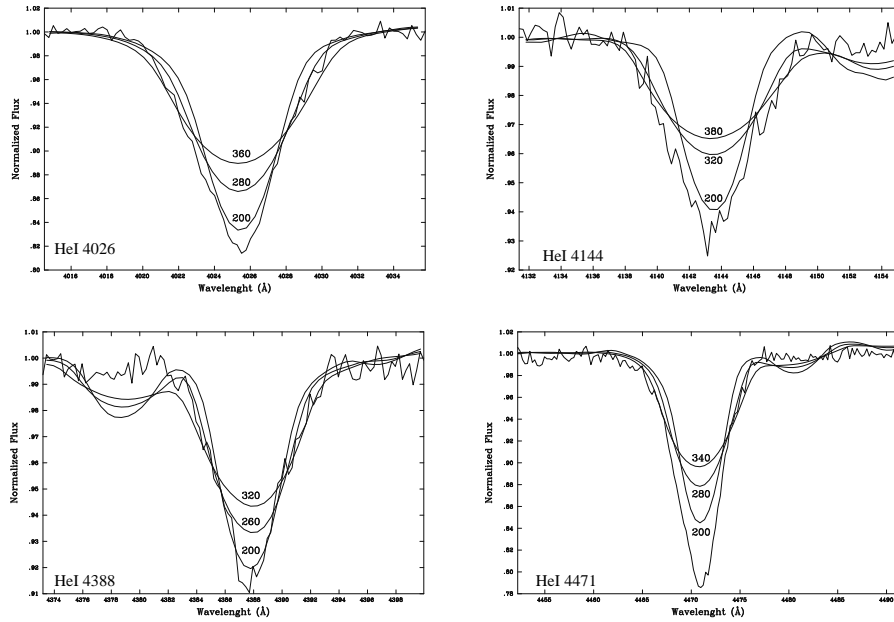


Fig. 12. Normalised profiles of selected He I lines (namely, He I $\lambda 4026$, $\lambda 4144$, $\lambda 4388$, and $\lambda 4471$ Å) from BD +53°2790 together with those of the same lines from 10 Lac but artificially broadened to 200 km s⁻¹ and to those rotational velocities yielding upper and lower envelopes to the width of the BD +53°2790 lines (their values are shown at the peak of the profile, in units of km s⁻¹). In all cases rotational velocities above 200 km s⁻¹ are needed to reproduce the line widths.

makes untenable a Be classification for the star. Based on a careful inspection to the source spectrum in the classification region and the peculiar behavior of the H α emission line, we conclude that the object is likely to be a single peculiar O-type star (O9.5Vp) and an early-type analogue to He-strong stars.

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References

- Andrillat, Y., Jaschek, M., & Jaschek, C. 1988, A&AS, 72, 129
- Andrillat, Y., Jaschek, M., & Jaschek, C. 1995, A&AS, 112, 475
- Balona, L., & Crampton, D. 1974, MNRAS, 166, 203
- Bjorkman J.E., & Cassinelli J.E. 1992, In: Nonisotropic and Variable Outflows from Stars, San Francisco, ASP Conference Series, 22, 88
- Blay P., Ribó M., Negueruela, I., et al. 2005, A&A, 438, 963
- Bohlender, D.A., Brown, D.N., Landstreet, J.D., & Thompson, I.B. 1987, ApJ, 323, 325
- Buscombe, W. 1969, MNRAS, 143, 1
- Clark, J.S., Lyuty, V.M., Zaitseva, G. V., et al. 1999, MNRAS, 302, 167
- Clark, J.S., Reig, P., Goodwin, S.P., et al. 2001a, A&A, 376, 476
- Clark, J.S., Tarasov, A.E., Okazaki, A.T., et al. 2001b, A&A, 380, 615
- Conti, P. S & Alschuler, W. R 1971, ApJ, 170, 325
- Corbet, R.H.D., & Peele, A.G. 2001, ApJ 562, 936
- Dachs, J., & Wamsteker, W. 1982, A&A, 107, 240
- Dachs J., Hanuschik, R., Kaiser, D., Rohe, D. 1986, A&A, 159, 276
- Donati, J.F., Babel, J., Harries, T.J., Howarth, I.D., Petit, P., & Semel, M. 2002, MNRAS, 333, 55

- Everall, C. 1995, Ph. D. Thesis, University of Southampton
- Everall, C., Coe, M.J., Norton, A.J., et al. 1993, MNRAS, 262, 57
- Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., & Tananbaum, H. 1972 ApJ., 178, 281
- Halbedel, E. M. 1993, PASP, 105, 465
- Hanuschik, R.W., Kozok, J.R., & Kaiser, D. 1988, A&A, 189, 147
- Herbig, G.H. 1975, ApJ, 196, 129
- Howarth, I., Murray, J., Mills, D., & Berry, D.S. 1997, Starlink User Note 50.20, R.A.L.
- Landolt, A. U. 1992, AJ, 104, 340
- Lee, U., Saio, H., Osaki, Y. 1991, MNRAS, 250, 432
- Manfroid, J. 1993, A&A, 271, 714
- Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
- Masetti, N., Dal Fiume, D., Amati, L., Del Sordo, S., Frontera, F., Orlandini, M., Palazzi, E. 2004, A&A, 423, 311
- Mathys, G. 1988, A&AS, 76, 427
- McSwain, M.V., & Gies, D.R. 2002, ApJ, 568, L27
- Negueruela, I., Okazaki, A.T., Fabregat, J., et al. 2001, A&A, 369, 117
- Negueruela, I., & Reig, P. 2001, A&A, 371, 1056
- Okazaki A.T., 2000a, In: Smith M., Henrichs H.F., Fabregat J. (eds.) IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, San Francisco, ASP Conf. Series, 214, 409
- Pedersen, H. & Thomsen, B. 1977, A&AS, 30, 11
- Perry, C.L., Olsen, D.H., & Crawford, D.J. 1987, PASP, 99, 1184
- Popper, D.M. 1980, ARA&A, 18, 115
- Porter, J.M. 1997 A&A, 324, 597
- Porter, J.M. 1999 A&A, 348, 512
- Reig, P., Negueruela, I., Coe, M.J., et al. 2000, MNRAS, 317, 205
- Reig, P., Ribó, M., Paredes, J. M., & Martí, J. 2003, A&A, 405, 285
- Ribó, M., Reig, P., Martí, J., & Paredes, J. M. 1999, A&A, 347, 518
- Ribó M., et al. 2005, A&A, submitted
- Saraswat, P., & Apparao, K. M. V. 1992, ApJ, 401, 678
- Shobbrook, R.R. 1983, MNRAS, 205, 1215
- Shortridge, K., Meyericks, H., Currie, M., et al. 1997, Starlink User Note 86.15, R.A.L
- Smith, M. A. & Fullerton, A. W. 2005, PASP, 117, 13
- Smith, M. A. & Groote, D. 2001, A&A, 372, 208
- Steiner, J.E., Ferrara, A., Garcia, M., et al. 1984, ApJ, 280, 688
- Torrejón, J. M., Kreykenbohm, I., Orr, A., Titarchuk, L., Negueruela, I. 2004 A&A, 423, 301
- Townsend, R.H.D. & Owocki, S.P. 2005, MNRAS, 357, 251
- Walborn, N.R. 1982, PASP, 94, 322
- Warwick, R. S., Marshall, N., Fraser, G. W. et al. 1981 MNRAS, 197, 865
- Zuiderwijk, E. J., Martin, R., Raimond, E., & van Diepen, G. N. J. 1994, PASP, 106, 515

Table 1. Strömgren photometry of the optical counterpart to 4U 2206+54. The last column indicates the telescope used. a stands for the 1.5-m Spanish telescope at Calar Alto. b represents the 1.23-m German telescope. c is the Skinakas 1.3-m telescope.

| Date | MJD | V | $(b - y)$ | m_1 | c_1 | β | T |
|--------------|-----------|-------------|-------------|--------------|--------------|-------------|---|
| 1988, Jan 7 | 47168.290 | 9.909±0.013 | 0.257±0.005 | -0.083±0.007 | 0.011±0.007 | 2.543±0.040 | a |
| 1989, Jan 4 | 74531.305 | 9.845±0.015 | 0.257±0.007 | -0.042±0.010 | -0.117±0.017 | 2.543±0.007 | a |
| 1991, Nov 16 | 48577.401 | 9.960±0.034 | 0.268±0.005 | -0.040±0.012 | -0.041±0.033 | — | b |
| 1991, Dec 19 | 48610.297 | 9.969±0.038 | 0.271±0.021 | -0.322±0.006 | -0.010±0.018 | 2.489±0.024 | b |
| 1994, Jun 21 | 49524.500 | 9.835±0.019 | 0.258±0.013 | -0.032±0.021 | 0.053±0.030 | 2.617±0.020 | b |
| 1996, May 26 | 50229.642 | 9.845±0.012 | 0.267±0.007 | -0.052±0.012 | -0.074±0.013 | 2.553±0.006 | a |
| 1999, Aug 16 | 51407.500 | 9.883±0.031 | 0.255±0.044 | -0.226±0.074 | 0.298±0.094 | — | c |

Table 4. Log of spectroscopic observations during 2000.

| Date | Tel | Configuration | Detector | λ Range (Å) |
|--------------|-----|-----------------------------------|----------|---------------------|
| Jul 17, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Jul 18, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Jul 19, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Jul 20, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Jul 21, 2000 | SKI | grating 1302 l/mm blazed at 4800Å | SITe | 3800 - 5700 |
| Jul 22, 2000 | SKI | grating 1302 l/mm blazed at 4800Å | SITe | 3800 - 5700 |
| Jul 25, 2000 | BOL | BFOSC + gr#6 | EEV | 3100 - 5300 |
| Jul 25, 2000 | BOL | BFOSC + gr#7 | EEV | 4200 - 6700 |
| Jul 25, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 26, 2000 | BOL | BFOSC + gr#6 | EEV | 3100 - 5300 |
| Jul 26, 2000 | BOL | BFOSC + gr#7 | EEV | 4200 - 6700 |
| Jul 26, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 27, 2000 | BOL | BFOSC + gr#6 | EEV | 3100 - 5300 |
| Jul 27, 2000 | BOL | BFOSC + gr#7 | EEV | 4200 - 6700 |
| Jul 27, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 28, 2000 | BOL | BFOSC + gr#6 | EEV | 3100 - 5300 |
| Jul 28, 2000 | BOL | BFOSC + gr#7 | EEV | 4200 - 6700 |
| Jul 28, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 29, 2000 | BOL | BFOSC + gr#6 | EEV | 3100 - 5300 |
| Jul 29, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 29, 2000 | BOL | BFOSC + gr#9+#10 | EEV | 3750 - 8000 |
| Jul 30, 2000 | BOL | BFOSC + gr#8 | EEV | 6100 - 8200 |
| Jul 30, 2000 | BOL | BFOSC + gr#9+#10 | EEV | 3750 - 8000 |
| Oct 05, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Oct 16, 2000 | SKI | grating 1302 l/mm blazed at 5500Å | SITe | 5520 - 7560 |
| Oct 17, 2000 | SKI | grating 1302 l/mm blazed at 4800Å | SITe | 3800 - 5700 |

Table 5. Log of spectroscopic observations. Some representative spectra are displayed in Fig. 2 (marked with ‘*’)

| Date | Tel | Configuration | Detector | λ Range (Å) | EW of H α (Å) |
|-----------------|------|---------------|----------|------------------------|-------------------------|
| May 28, 1986(*) | INT | IDS + 500 mm | GEC1 | 6450 – 6830 | -5.87 ± 0.17 |
| Jul 26, 1986(*) | INT | IDS + 500 mm | GEC1 | 6495 – 6695 | -3.40 ± 0.20 |
| Aug 03, 1986 | INT | IDS + 235 mm | IPCS | 6010 – 7020 | -5.20 ± 1.50 |
| Aug 04, 1986 | INT | IDS + 235 mm | IPCS | 6010 – 7020 | -6.00 ± 0.90 |
| Sep 07, 1986 | INT | IDS + 235 mm | GEC1 | 4000 – 8000 | |
| Oct 09, 1986(*) | INT | IDS + 500 mm | GEC1 | 6465 – 6665 | -7.30 ± 0.40 |
| Dec 24, 1986(*) | INT | IDS + 500 mm | GEC1 | 6250 – 6875 | -1.30 ± 0.11 |
| Jun 12, 1987 | INT | IDS + 235 mm | GEC1 | 6330 – 6770 | -1.62 ± 0.18 |
| Jun 20, 1987 | INT | IDS + 235 mm | GEC1 | 6080 – 6900 | -1.47 ± 0.21 |
| Aug 13, 1987(*) | INT | IDS + 500 mm | GEC1 | 6375 – 6765 | -2.10 ± 0.21 |
| Aug 28, 1987 | INT | IDS + 235 mm | GEC1 | 6340 – 6770 | -2.19 ± 0.22 |
| Sep 08, 1987 | INT | IDS + 500 mm | GEC1 | 6340 – 6730 | -2.01 ± 0.12 |
| May 19, 1988 | INT | IDS + 500 mm | IPCS | 6240 – 6720 | -1.31 ± 0.19 |
| Aug 02, 1988(*) | INT | IDS + 235 mm | GEC4 | 6230 – 6860 | -2.90 ± 0.40 |
| Sep 26, 1988 | INT | IDS + 500 mm | GEC4 | 6455 – 6655 | -1.49 ± 0.25 |
| Oct 12, 1988 | INT | IDS + 500 mm | GEC4 | 6325 – 6950 | -0.96 ± 0.17 |
| Jun 02, 1989 | INT | IDS + 235 mm | IPCS | 6230 – 6875 | -1.80 ± 0.40 |
| Jun 11, 1989 | INT | IDS + 235 mm | IPCS | 5970 – 7010 | -2.10 ± 0.60 |
| Jul 31, 1989(*) | INT | IDS + 235 mm | IPCS | 6205 – 6870 | -1.54 ± 0.30 |
| Jul 24, 1990 | INT | IDS + 235 mm | GEC6 | 6350 – 6780 | -2.83 ± 0.26 |
| Sep 02, 1990 | INT | IDS + 235 mm | GEC6 | 6345 – 6775 | -2.55 ± 0.38 |
| Dec 27, 1990 | INT | IDS + 500 mm | GEC6 | 6470 – 6670 | -3.20 ± 0.30 |
| Aug 28, 1991(*) | INT | IDS + 500 mm | GEC6 | 6480 – 6680 | -1.12 ± 0.18 |
| May 18, 1992(*) | PAL | f/8.75 Cass | CCD9 | 6255 – 6938 | $+1.38 \pm 0.13$ |
| May 19, 1992 | PAL | f/8.75 Cass | CCD9 | 6522 – 6663 | $+0.13 \pm 0.05$ |
| Aug 16, 1992(*) | PAL | f/8.75 Cass | CCD9 | 6255 – 6930 | -2.30 ± 0.40 |
| Aug 17, 1992 | PAL | f/8.75 Cass | CCD9 | 6255 – 6930 | -2.14 ± 0.30 |
| Aug 18, 1992 | PAL | f/8.75 Cass | CCD9 | 6255 – 6930 | -2.23 ± 0.30 |
| Sep 23, 1993(*) | PAL | f/8.75 Cass | CCD9 | 6280 – 6960 | -1.78 ± 0.30 |
| Dec 05, 1993 | PAL | f/8.75 Cass | CCD9 | 6259 – 6936 | -1.64 ± 0.19 |
| Dec 06, 1993 | PAL | f/8.75 Cass | CCD9 | 4300 – 5000 | |
| Dec 07, 1993 | PAL | f/8.75 Cass | CCD9 | 6260 – 6940 | -1.69 ± 0.15 |
| Mar 26, 1994 | JKT | RBS | EEV7 | 5700 – 6710 | -0.88 ± 0.18 |
| Mar 27, 1994 | JKT | RBS | EEV7 | 5700 – 6710 | -0.87 ± 0.15 |
| Jun 25, 1994 | JKT | RBS | EEV7 | 4200 – 5200 | |
| Jun 26, 1994 | JKT | RBS | EEV7 | 6070 – 7040 | -1.19 ± 0.21 |
| Jun 27, 1994 | JKT | RBS | EEV7 | 4200 – 5200 | |
| Sep 16, 1994(*) | JKT | RBS | EEV7 | 5825 – 6890 | -2.28 ± 0.24 |
| Sep 16, 1994 | JKT | RBS | EEV7 | 8100 – 9100 | |
| Sep 17, 1994 | JKT | RBS | EEV7 | 3900 – 4950 | |
| Jul 11, 1995 | INT | IDS + 235 mm | TEK3 | 4080 – 4940 | |
| Jul 12, 1995(*) | INT | IDS + 235 mm | TEK3 | 6430 – 7286 | -2.00 ± 0.30 |
| Aug 04, 1995 | JKT | RBS | TEK4 | 6360 – 7265 | -2.20 ± 0.40 |
| Aug 04, 1995 | JKT | RBS | TEK4 | 8200 – 9000 | |
| Aug 05, 1995 | JKT | RBS | TEK4 | 4100 – 5050 | |
| Aug 06, 1995 | JKT | RBS | TEK4 | 6420 – 6755 | -1.51 ± 0.25 |
| Aug 07, 1995 | JKT | RBS | TEK4 | 4000 – 4450 | |
| Sep 22, 1995 | CRAO | Coude | EEV15–11 | 4400 – 4950 | |
| Nov 29, 1995 | JKT | RBS | TEK4 | 6100 – 6900 | -2.30 ± 0.40 |
| Jun 30, 1997 | CRAO | Coude | EEV15–11 | 4200 – 5100 | |
| Oct 26, 1997 | JKT | RBS | TEK4 | 5904 – 6818 | -1.77 ± 0.32 |
| Oct 27, 1997 | JKT | RBS | TEK4 | 8200 – 9000 | |
| Oct 28, 1997(*) | JKT | RBS | TEK4 | 6380 – 6720 | -1.47 ± 0.25 |
| Aug 03, 1998 | INT | IDS + 235 mm | EEV42 | 3700 – 5050 | |
| Aug 04, 1998(*) | INT | IDS + 235 mm | EEV42 | 5800 – 7100 | -1.87 ± 0.30 |
| Aug 31, 1998 | CRAO | Coude | EEV15–11 | 6530 – 6600 | -1.49 ± 0.02 |
| Aug 31, 1998 | CRAO | Coude | EEV15–11 | 6645 – 6620 | |

Continued...

Table 5: Continued.

| Date | Tel | Configuration | Detector | λ Range (Å) | EW of H α (Å) |
|-----------------|-----|------------------------------------|--------------|------------------------|-------------------------|
| Jul 26, 1999 | SKI | 1201 line mm ⁻¹ grating | ISA SiTe CCD | 5520 – 7560 | -2.89 ± 0.07 |
| Aug 17, 1999(*) | BOL | BFOSC + gr#9+#12 | Loral | 5300 – 9000 | -1.35 ± 0.40 |
| Aug 17, 1999 | BOL | BFOSC + gr#7 | Loral | 4200 – 6700 | |
| Aug 22, 1999 | BOL | BFOSC + gr#8 | Loral | 6100 – 8200 | -1.85 ± 0.10 |
| Aug 22, 1999 | BOL | BFOSC + gr#7 | Loral | 4200 – 6700 | |

Table 6. Observational details, IR photometry.

| Date | MJD | J | H | K | L' | Telescope |
|--------------|---------|-----------|-----------|-----------|-----------|-----------|
| Sep 06, 1987 | 47044.5 | 9.37±0.03 | 9.26±0.03 | 9.09±0.03 | 9.0±0.4 | TCS |
| Sep 11, 1987 | 47049.5 | 9.70±0.04 | 9.48±0.04 | 9.28±0.04 | | TCS |
| Nov 24, 1987 | 47123.5 | 9.16±0.03 | 9.08±0.03 | 8.92±0.03 | 8.71±0.06 | UKIRT |
| Dec 28, 1987 | 47157.5 | 9.26±0.03 | 9.16±0.03 | 9.06±0.03 | | TCS |
| Jan 01, 1988 | 47161.5 | 9.28±0.04 | 9.10±0.04 | 8.99±0.04 | 8.8±0.4 | TCS |
| Jan 03, 1988 | 47163.5 | 9.24±0.03 | 9.08±0.03 | 8.97±0.03 | 8.8±0.3 | TCS |
| Jun 23, 1988 | 47335.5 | 9.28±0.04 | 9.17±0.04 | 9.01±0.04 | | TCS |
| Jun 24, 1988 | 47336.5 | 9.25±0.03 | 9.15±0.03 | 8.98±0.03 | | TCS |
| Jun 28, 1988 | 47340.5 | 9.16±0.04 | 9.11±0.04 | 9.00±0.04 | | TCS |
| Apr 14, 1991 | 48360.5 | 9.25±0.02 | 9.12±0.03 | 9.05±0.02 | | TCS |
| Apr 17, 1991 | 48363.5 | 9.26±0.06 | 9.12±0.03 | 9.03±0.02 | | TCS |
| Aug 23, 1991 | 48491.5 | 9.22±0.03 | 9.08±0.02 | 9.01±0.02 | | TCS |
| Aug 24, 1991 | 48492.5 | 9.16±0.09 | 9.04±0.05 | 9.00±0.05 | | TCS |
| Aug 25, 1991 | 48493.5 | 9.18±0.04 | 9.05±0.03 | 8.95±0.03 | | TCS |
| Aug 27, 1991 | 48495.5 | 9.17±0.03 | 9.06±0.02 | 9.00±0.03 | | TCS |
| Aug 28, 1991 | 48496.5 | 9.19±0.04 | 9.05±0.03 | 8.98±0.05 | | TCS |
| Nov 29, 1991 | 48589.5 | 9.30±0.10 | 9.10±0.10 | 9.00±0.10 | | TCS |
| Dec 01, 1991 | 48591.5 | 9.24±0.05 | 9.08±0.04 | 9.01±0.04 | | TCS |
| Jul 20, 1992 | 48823.5 | 9.22±0.03 | 9.11±0.03 | 8.98±0.05 | | TCS |
| Aug 04, 1992 | 48838.5 | 9.33±0.09 | 9.09±0.04 | 8.93±0.05 | | TCS |
| Aug 21, 1992 | 48855.5 | 9.29±0.04 | 9.07±0.03 | 9.03±0.06 | | TCS |
| Aug 21, 1992 | 48855.5 | 9.25±0.05 | 9.07±0.03 | 8.94±0.06 | | TCS |
| Aug 22, 1992 | 48856.5 | 9.14±0.06 | 9.04±0.04 | 9.07±0.04 | | TCS |
| Aug 23, 1992 | 48857.5 | 9.29±0.07 | 9.16±0.09 | 9.11±0.06 | | TCS |
| Jan 12, 1993 | 48999.5 | 9.20±0.03 | 9.07±0.01 | 8.98±0.02 | | TCS |
| Jun 22, 1993 | 49160.5 | 9.23±0.01 | 9.17±0.01 | 9.09±0.01 | 8.91±0.03 | UKIRT |
| Jun 30, 1993 | 49169.5 | 9.27±0.03 | 9.14±0.02 | 9.02±0.02 | 8.9±0.3 | UKIRT |
| Jul 06, 1993 | 49175.5 | 9.26±0.02 | 9.14±0.03 | 9.03±0.02 | 8.9±0.2 | UKIRT |
| Jul 07, 1993 | 49176.5 | 9.26±0.03 | 9.15±0.02 | 9.05±0.03 | | UKIRT |
| Dec 20, 1993 | 49341.5 | 9.11±0.01 | 9.11±0.01 | 8.95±0.02 | | TCS |
| Dec 20, 1993 | 49341.5 | 9.11±0.01 | 9.08±0.01 | 8.93±0.01 | | TCS |
| Dec 20, 1993 | 49341.5 | 9.18±0.03 | 9.06±0.01 | 8.99±0.06 | | TCS |
| Dec 21, 1993 | 49342.5 | 9.26±0.02 | 9.18±0.01 | 9.09±0.03 | | TCS |
| Dec 21, 1993 | 49342.5 | 9.27±0.03 | 9.13±0.01 | 9.13±0.01 | | TCS |
| Jun 08, 1994 | 49511.5 | 9.16±0.02 | 9.16±0.01 | 9.01±0.01 | | TCS |
| Jun 09, 1994 | 49512.5 | 9.28±0.01 | 9.13±0.02 | 9.06±0.03 | | TCS |
| Jun 10, 1994 | 49513.5 | 9.16±0.03 | 9.07±0.01 | 9.04±0.03 | | TCS |
| Jun 11, 1994 | 49514.5 | 9.24±0.06 | 9.28±0.04 | 9.17±0.05 | | TCS |
| Jun 21, 1994 | 49524.5 | 9.22±0.01 | 9.12±0.01 | 9.03±0.01 | | TCS |
| Jun 26, 1994 | 49529.5 | 9.22±0.02 | 9.14±0.01 | 9.06±0.03 | | TCS |
| Jun 28, 1994 | 49531.5 | 9.22±0.01 | 9.15±0.01 | 9.03±0.01 | | TCS |
| Jun 30, 1994 | 49533.5 | 9.24±0.01 | 9.09±0.02 | 9.08±0.02 | | TCS |
| Jul 01, 1994 | 49534.5 | 9.17±0.01 | 9.12±0.01 | 8.99±0.00 | | TCS |
| Jul 02, 1994 | 49535.5 | 9.26±0.02 | 9.20±0.01 | 9.09±0.01 | | TCS |
| Jul 03, 1994 | 49536.5 | 9.27±0.02 | 9.17±0.01 | 9.12±0.01 | | TCS |
| Nov 05, 1994 | 49661.5 | 9.16±0.01 | 9.09±0.01 | 9.06±0.01 | | TCS |
| Nov 06, 1994 | 49662.5 | 9.01±0.01 | 8.94±0.01 | 8.90±0.01 | | TCS |
| Nov 07, 1994 | 49663.5 | 9.28±0.02 | 9.21±0.01 | 9.14±0.02 | | TCS |
| Nov 08, 1994 | 49664.5 | 9.29±0.02 | 9.18±0.01 | 9.08±0.00 | | TCS |
| Nov 09, 1994 | 49665.5 | 9.21±0.01 | 9.11±0.01 | 9.08±0.01 | | TCS |
| Jan 02, 1995 | 49719.5 | 9.23±0.01 | 9.15±0.01 | 9.03±0.01 | | TCS |
| Jan 03, 1995 | 49720.5 | 9.12±0.01 | 9.07±0.01 | 9.00±0.01 | | TCS |
| Jan 05, 1995 | 49722.5 | 9.14±0.02 | 9.09±0.01 | 8.99±0.01 | | TCS |
| Apr 24, 1995 | 49831.5 | 9.16±0.01 | 9.07±0.01 | 9.02±0.02 | | TCS |
| Apr 25, 1995 | 49832.5 | 9.21±0.01 | 9.12±0.01 | 9.07±0.00 | | TCS |
| Apr 26, 1995 | 49833.5 | 9.25±0.01 | 9.13±0.01 | 9.03±0.01 | | TCS |

Continued...

Table 6: Continued.

| Date | MJD | J | H | K | L' | Telescope |
|--------------|---------|-----------|-----------|-----------|----|-----------|
| Apr 28, 1995 | 49835.5 | 9.23±0.01 | 9.14±0.01 | 9.05±0.01 | | TCS |
| Apr 29, 1995 | 49836.5 | 9.20±0.01 | 9.08±0.01 | 9.04±0.01 | | TCS |
| Jul 28, 1995 | 49926.5 | 9.22±0.02 | 9.12±0.01 | 9.09±0.15 | | TCS |
| Jul 28, 1995 | 49926.5 | 9.23±0.01 | 9.04±0.01 | 9.60±0.13 | | TCS |
| Jul 29, 1995 | 49927.5 | 9.18±0.01 | 9.06±0.01 | 8.94±0.06 | | TCS |
| Jul 29, 1995 | 49927.5 | 9.19±0.01 | 9.04±0.01 | 9.09±0.11 | | TCS |
| Jul 31, 1995 | 49929.5 | 9.27±0.01 | 9.10±0.01 | 8.95±0.01 | | TCS |
| Oct 11, 1995 | 50001.5 | 9.36±0.01 | 9.17±0.01 | 9.00±0.00 | | TCS |
| Oct 14, 1995 | 50004.5 | 9.15±0.01 | 9.03±0.01 | 8.90±0.01 | | TCS |
| Jul 27, 1996 | 50291.5 | 9.40±0.01 | 9.25±0.01 | 9.07±0.00 | | TCS |
| Jul 28, 1996 | 50292.5 | 9.14±0.01 | 9.03±0.01 | 8.92±0.01 | | TCS |
| Jul 16, 1997 | 50645.5 | 9.20±0.01 | 9.09±0.01 | 8.98±0.01 | | TCS |
| Jul 17, 1997 | 50646.5 | 9.18±0.01 | 9.06±0.01 | 8.96±0.01 | | TCS |
| Jul 19, 1997 | 50648.5 | 9.17±0.01 | 9.07±0.01 | 8.99±0.00 | | TCS |
| Jun 15, 1998 | 50979.5 | 9.16±0.01 | 9.09±0.01 | 8.98±0.01 | | TCS |
| Jun 16, 1998 | 50980.5 | 9.12±0.01 | 9.07±0.01 | 8.98±0.01 | | TCS |
| Jun 17, 1998 | 50981.5 | 9.19±0.01 | 9.10±0.01 | 8.99±0.00 | | TCS |
| Oct 27, 1998 | 51113.5 | 9.29±0.01 | 9.17±0.01 | 9.13±0.00 | | TCS |
| Jul 26, 1999 | 51385.5 | 9.23±0.02 | 9.12±0.02 | 9.09±0.02 | | TCS |
| Jul 28, 1999 | 51387.5 | 9.20±0.02 | 9.13±0.02 | 9.05±0.02 | | TCS |
| Jul 31, 1999 | 51390.5 | 9.22±0.02 | 9.13±0.02 | 9.06±0.02 | | TCS |
| Oct 02, 1999 | 51453.5 | 9.18±0.02 | 9.08±0.02 | 8.98±0.02 | | TCS |
| Oct 04, 1999 | 51455.5 | 9.20±0.02 | 9.10±0.02 | 9.03±0.02 | | TCS |
| Oct 05, 1999 | 51456.5 | 9.20±0.02 | 9.13±0.01 | 9.02±0.02 | | TCS |
| Jan 15, 2001 | 51924.5 | 9.20±0.02 | 9.08±0.02 | 8.96±0.02 | | TCS |